

Hydraulic characteristics of a rectangular mixed-cell rearing unit

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Abstract

We describe a fish rearing unit modification that establishes mixed flow reactor (MFR) behavior in a rectangular vessel so as to eliminate metabolite concentration gradients, increase current velocities and improve solids scour at low water exchange rates. A standard raceway section 14.5 m long was modified to create six counter-rotating mixed cells, each 2.4 m wide by 2.4 m long. Cells receive water from vertical pipe sections extending to the tank floor and positioned in the corners of the cells. Vertical pipe sections were fabricated with jet ports that direct water into the cells tangentially to establish rotary circulation. Water exits each cell through a centrally located floor drain. Hydraulic characteristics of the tank are described based on an analysis of residence time distribution, current velocities and cell-to-cell water exchange rates. The latter was calculated based on a proposed hydraulics model and tracer concentrations established at a steady state. Vessel dispersion numbers measured with water exchange rates of 1.0 and 1.3 per hour, indicate tank performance approximates that of a MFR with the active tank volume representing 77.9–100% of total tank volume. Water velocities measured at 216 stations averaged 0.14, 0.12 and 0.12 m/s for the tank surface, mid-depth and near bottom regions. The benthic shear stress calculated given surface velocity was 0.04 N/m². This was sufficient to scour and purge fecal solids produced by 2010 kg of lake trout that averaged 44.3 cm in total length. Cell interaction was significant

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with cell-to-cell exchange rates averaging 3.9 times the tank inflow rate. Energy requirements of the rearing unit were kept low (1.32 m water gauge pressure; 6.7 W/m³) through use of a large number of low velocity jets. © Published by Elsevier Science B.V.

Keywords: Rearing unit; Hydraulics; Salmonidae; Mixed flow reactor; Design; Raceway

Nomenclature

C_i	tracer concentration in effluent at time i (mg/l)
C_{\min}	tracer concentration in influent following step down (mg/l)
CER	cell exchange rate (l/min)
D	dispersion coefficient (m ² /sec)
d	particle diameter (mm)
$D/\mu L$	vessel dispersion number (dimensionless)
e	combined pump and motor efficiency (0.7, dimensionless)
G	specific gravity (dimensionless)
H	hydraulic gradient (m)
L	characteristic length (m)
MD	mass tracer discharged (mg/min)
NF	net flux of tracer (mg/min)
P	power (W/m ³)
Q	water flow rate (l/min)
T	temperature (°C)
TL	fish length (cm)
t	time (min)
\bar{t}	theoretical mean residence time, V/Q (min)
t_c	calculated mean residence time (min)
SR	stagnant region (dimensionless)
V	tank volume (l)
V_{safe}	allowable current velocity (body lengths/s)
V_{sc}	required scouring velocity (ft/s)
X	cell number (dimensionless)
Y	normalized tracer concentration ($\Delta C/\Delta C_{\max}$)
ΔC_{\max}	maximum change (negative) in tracer concentration (mg/l)
γ	specific weight of water (N/m ³)
μ	fluid velocity (m/s)
μ^*	shear velocity (m/s)
θ	normalized time, t/\bar{t} (dimensionless)
σ^2	variance about t_c (min)

1. Introduction

Rearing unit design affects fish performance as well as system maintenance costs (Burrows and Chenoweth, 1970; Ross et al., 1995). Of particular importance is the ability of the design to circumvent problems associated with the accumulation of fecal solids or uneaten feed. Failure to remove this material can result in secondary production of ammonia, an increase in oxygen demand, and the development of suspended solids concentrations that predispose fish to bacterial gill disease and other infections (Stickney, 1979; Wickins, 1980). High water exchange rates are required for self-cleaning action in linear raceways (Westers and Pratt, 1977; Youngs and Timmons, 1991) dictating reuse of water. Water reuse promotes disease transmission as well as a gradient in dissolved oxygen and fish metabolites along the axis of the rearing unit series. Deteriorating water quality results in fish mortality and growth differences among individual rearing units and as such is undesirable (Watten and Johnson, 1990). Past attempts to improve the self-cleaning characteristics of the raceways through use of vertical baffles have been only partially successful (Boerson and Westers, 1986; Kindschi et al., 1991; Barnes et al., 1996).

Circulating rearing units such as the circular (Larmoyeux et al., 1973; Burrows and Chenoweth, 1955; Timmons et al., 1998), Swedish (Piper et al., 1982), and square types (Burley and Klapsis, 1985) are operated as mixed flow reactors designed to avoid the problems outlined above. Jetting influent water tangentially establishes a circulating flow that provides a more homogeneous water column, greater self-cleaning action at relatively low water exchange rates, and substantial current velocities for improvements in fish performance (Burrows, 1969; Besner and Smith, 1983; Leon, 1986). Recently, a cross-flow vessel has been developed that incorporates the rectangular shape of linear raceways while providing the hydraulic characteristics of the circulating rearing units (Watten and Johnson, 1990). Water is introduced along one side of the tank and collected at floor level along the opposite side. Here, the influent is jetted across the floor to prevent the accumulation of particulate matter and to establish rotary circulation about the longitudinal axis. Field trials have been positive (Watten and Johnson, 1990; Ross et al., 1995; Ross and Watten, 1998), but tank construction costs are high. We describe an alternative method for modifying linear raceways to establish mixed flow reactor behavior. Design changes include use of screened floor drains positioned along the longitudinal axis of the tank and water jets positioned to establish a series of adjacent counter rotating mixed cells. The hydraulic characteristics of a test tank measuring 14.5 m long by 2.4 m wide are described based on an analysis of fluid residence time distribution (RTD), measurement of current velocities and cell-to-cell water exchange rates.

2. Tank design

A standard concrete raceway section was modified to create six counter-rotating mixed cells, each 2.4 m wide by 2.4 m long (Fig. 1). Cells received water from

vertical pipe sections extending to the tank floor and positioned in the corners of the cells. Vertical pipe sections serving two adjacent cells were constructed with eight jet ports, whereas pipe sections serving a single cell were constructed with four jet ports. The jet ports ($N = 76$) were 6.35 mm in diameter and oriented so as to direct water into the cells tangentially to establish rotary circulation. The vertical pipe sections were coupled with 10 cm diameter influent manifolds using threaded elbows. Influent manifolds ran along the top and length of both walls of the tank. This allowed vertical pipe sections to be swung up and out of the water during fish crowding or grading operations. Influent manifolds, vertical pipe sections and jet

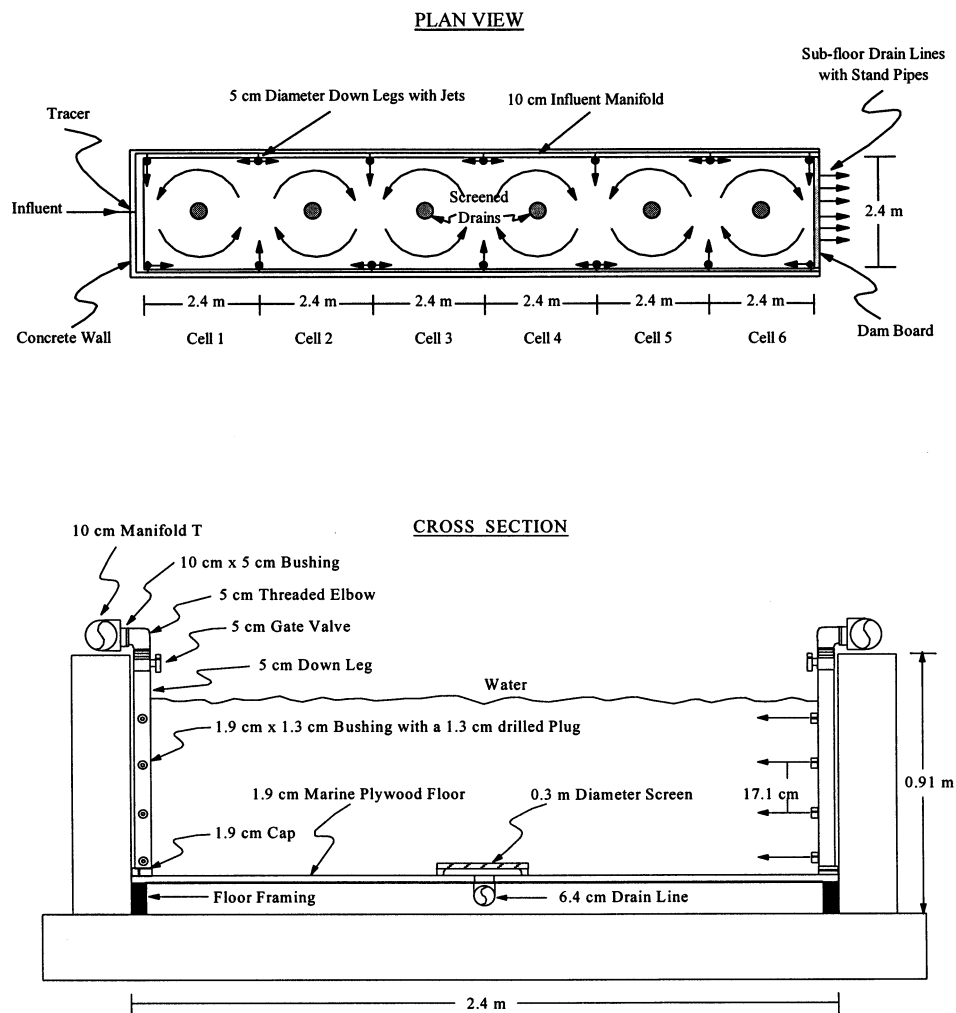


Fig. 1. Plan and section view of the test rectangular mixed cell rearing unit.

orifice designs were based on theoretical considerations given by Van Der Hegge Zijnen (1951), and Acrivos et al. (1959).

Water exited each cell through a centrally located floor drain measuring 6.4 cm in diameter, then was routed independently through the damboard end of the tank for final discharge. Each floor drain was covered by a screen measuring 0.3 m in diameter and constructed using perforated aluminum sheet stock. The sheet stock was fastened to a ring of plastic pipe slotted so as to fix the screen 2.5 cm above the tank floor. The water flow rate through each of the six drain lines was regulated by adjusting the height of external standpipes. Drain lines within the tank were covered by a false tank floor constructed of marine grade plywood, sealed with white epoxy paint and supported by 5 × 10 cm wood framing. We refer to this new design as a rectangular mixed-cell rearing unit.

3. Materials and methods

3.1. Background

Hydraulic behavior was evaluated by analysis of RTD and measurement of current directions and velocities. The RTD analysis is used to characterize nonideal flow in process reactors (Danckwerts, 1953) and requires a pulse or step change in an influent tracer (nonreactive) concentration. Monitoring the response of the effluent and developing a rectangular-coordinate plot of tracer concentration versus time establishes the exit-age distribution of material flowing through the vessel. Flow anomalies can then be identified as well as the mean residence time of a fluid element (\bar{t}_c) within the vessel, the dispersion about the mean (σ^2) and the degree of axial dispersion or mixing ($D/\mu L$). The group $D/\mu L$, termed the vessel dispersion number, changes in value from zero for ideal plug flow to infinity for completely mixed flow reactor behavior (Levenspiel, 1979). Regarding flow anomalies, a \bar{t}_c less than the theoretical retention time (\bar{t}) establishes the presence of stagnant regions (SR) within the reactor. The extent of these regions expressed as a fraction of the reactors total liquid volume is:

$$SR = 1 - \bar{t}_c / \bar{t} \quad (1)$$

where

$$\bar{t} = V/Q \quad (2)$$

With a step down in tracer concentration, \bar{t}_c and σ^2 are defined as follows (Levenspiel, 1979):

$$\bar{t}_c = \frac{\int_0^\infty (C_{\min} - C_i) dt}{\Delta C_{\max}} \quad (3)$$

$$\sigma^2 = 2 \frac{\int_0^\infty t (C_{\min} - C_i) dt}{\Delta C_{\max}} - \bar{t}_c^2 \quad (4)$$

Given \bar{t}_c and σ^2 , $D/\mu L$ is calculated by using the expression (Levenspiel, 1979):

$$\frac{\sigma^2}{\bar{t}_c^2} = 2 (D/\mu L) - 2 (D/\mu L)^2 [1 - \exp^{-\mu L/D}]. \quad (5)$$

3.2. Analyses

The RTD analysis was performed at a flow rate of 379 l/min (about 1 exchange/h) with and without 2010 kg of lake trout (*Salvelinus namaycush*) present in the tank. The trout averaged 44.3 cm in total length, 895 g in weight and were held in the test tank 148 days prior to the RTD runs. The RTD analysis was also performed at a flow rate of 502 l/min (about 1.3 exchanges/h) without fish present. RTD analyses were replicated three times for each set of operating conditions tested. Well water (10°C) was used in all runs. Flow rate exiting each cell was measured using a stopwatch and container of known capacity. Water line pressure (gage) was measured with a water filled u-tube manometer. RTD was identified based on a step down in tracer concentration from one steady value to another (Watten and Beck, 1987; Watten and Johnson, 1990). Chloride ion (Cl^-) was used as the nonreactive tracer. A salt (NaCl) solution was dispersed in the water supply manifold at a rate that provided about a 15 fold increase in Cl^- concentration above the average influent level of 3 mg/l. Brine flow was provided by a peristaltic pump operating at a constant speed. The step down in tracer concentration was achieved by terminating brine flow allowing tank influent Cl^- concentrations to return to the normal water supply level. Samples of individual tank cell effluents were then taken concurrently at 8 min intervals using autosamplers (Model 1350 American Sigma, Medina, NY). Chloride concentrations were determined using high pressure liquid chromatography (APHA, 1989). Following data collection SR, \bar{t}_c , σ^2 , and $D/\mu L$ were calculated based on Eqs. (1)–(5).

We characterized the exchange of water between adjacent tank cells by metering brine at a fixed rate into one of four manifolds serving cell 1. Chloride levels in all cells were then measured once steady-state conditions were established. Here the water flow rate was fixed first at about 516 l/min (about 1.3 exchanges/h) and in a second test series at 370 l/min (about 1 exchange/h). Water flow and Cl^- were measured as in the RTD analyses. These tests were replicated twice. Additionally, current velocities were measured at 216 stations distributed uniformly within tank cells 4, 5 and 6 at tank surface, mid-depth, and near-bottom (30 mm above floor). The water flow rate during this test was 510 l/min (about 1.3 exchanges/h). Velocities were measured by using an electromagnetic current meter (Marsh-McBirney Model 201D). Corresponding energy requirements (W/m^3) for the tank were calculated using the equation:

$$P = \frac{H\gamma (Q/60\,000)}{\text{eV}} \quad (6)$$

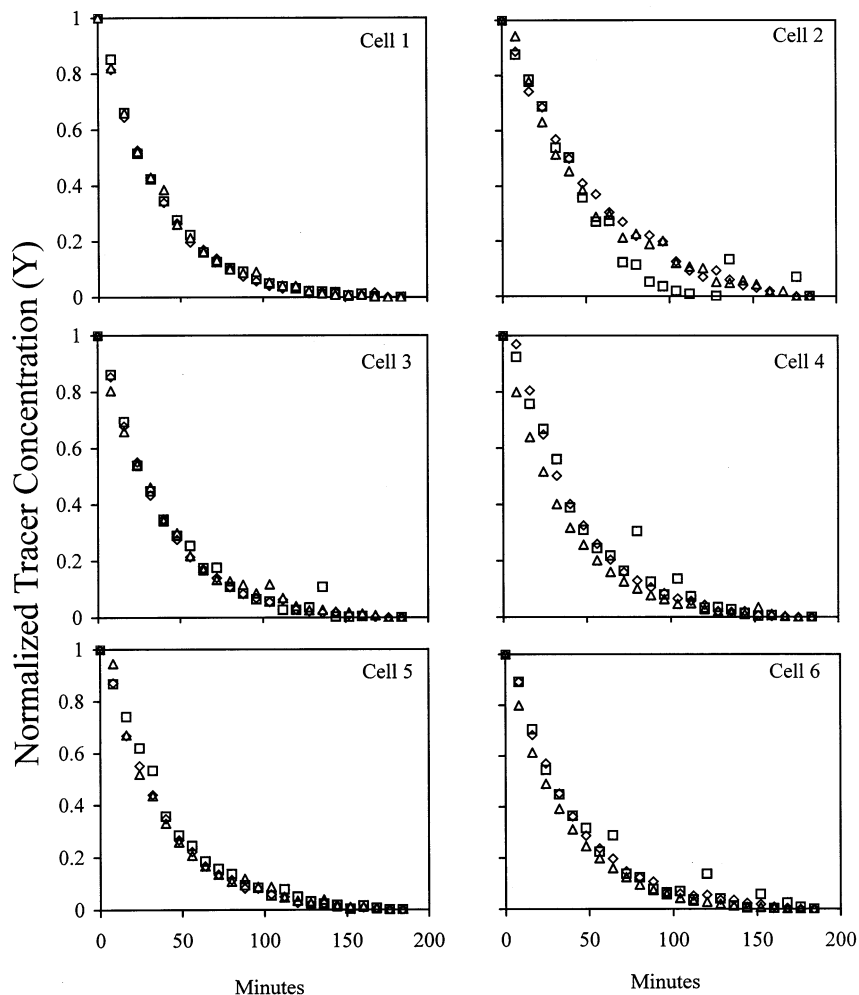


Fig. 2. Normalized tracer concentration plotted against time for the RTD analyses conducted at 1 exchange/h with lake trout present in the tank. Replicates are indicated by symbol type.

Benthic shear stress (μ^*), used to establish particulate matter scour potential, was calculated given mean surface velocity, water depth, surface roughness and water density (Peterson, 1999). Analysis of variance (ANOVA), Student's t and paired t analyses were used to test for factor effects and interactions with $\alpha = 0.05$. Analyses were performed using SigmaStat[®] 2.0 statistical software (SPSS Inc., Chicago, IL).

4. Results and discussion

The raceway modification tested was successful in establishing a linear series of

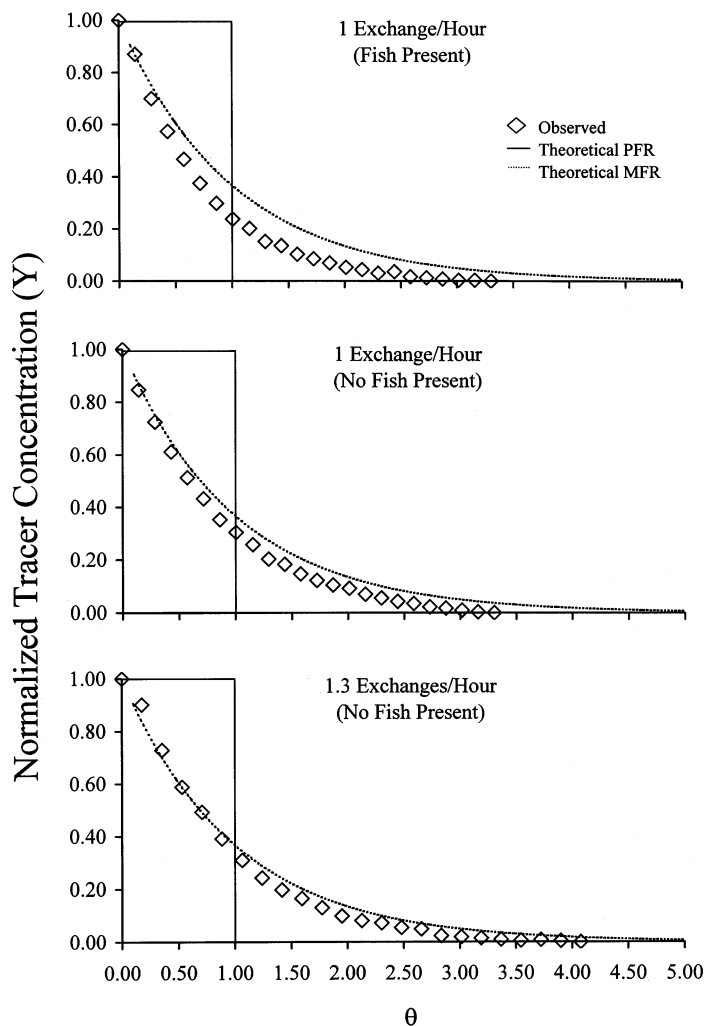


Fig. 3. Example overall tank effluent response to the step down in tracer concentration at 1 exchange/h (lake trout present), 1 exchange/h (no fish present) and at 1.3 exchanges/h (no fish present).

counter rotating mixed cells despite the absence of physical barriers along adjacent cell boundaries. With shading, lake trout distributed themselves throughout the tank volume and fecal material was purged quickly eliminating the need for manual solids removal. However, similar to raceways, periphyton and slime growth occurred on tank walls but growth was slow and the required cleaning frequency (every 60–90 days) was considered acceptable. Fig. 2 gives cell-by-cell summaries of the RTD data established at 1 exchange/h with lake trout present. Similar plots were established for all other tests conducted at 1 and 1.3 exchanges/h. Data were plotted using a normalized value of tracer concentration ($\Delta C/\Delta C_{\max}$) versus time.

Table 1

Residence time distribution characteristics \pm S.E. of the mixed cell tank conducted at 1 exchange/h (with and without lake trout present in the tank), and at 1.3 exchange/h (data represent the mean of three observations^a)

Variable	Exchange rate		
	1 Exchange/h — fish	1 Exchange/h — no fish	1.3 Exchange/h — no fish
Mean residence time, \bar{t}_c (min.)	44.1 \pm 0.4 ^b	49.0 \pm 1.0 ^c	45.6 \pm 0.4 ^b
Mean ratio \bar{t}_c / \bar{t} , (%)	76.9 \pm 0.7 ^b	79.7 \pm 1.2 ^b	100.4 \pm 0.6 ^c
Mean variance σ^2 (min ²)	776.8 \pm 31.4 ^b	1200.6 \pm 61.0 ^c	863.6 \pm 61.5 ^b
Mean ratio σ^2 / \bar{t}_c (min)	17.6 \pm 0.6 ^b	24.5 \pm 0.8 ^c	19.0 \pm 1.2 ^b
Mean dispersion number, $D/\mu L$ (dimensionless)	0.27 \pm 0.01 ^b	0.39 \pm 0.01 ^c	0.29 \pm 0.02 ^b

^a Values in the same row processing a common letter do not differ at 95% confidence level.

In each cell, the decrease of Cl^- concentration observed was described by an exponential model (R^2 , 0.79–0.86), with good agreement among replicates. Hydraulic retention time based on a combined cell discharge was normalized by dividing the observed time t by the theoretical retention time \bar{t} (Eq. (2)). In tests involving fish, a conversion factor of 0.982 liters per kg biomass was used to correct the calibrated tank volume for the volume displaced by biomass (Watten and Beck, 1987). Normalizing time allows comparison of the RTD with that predicted for an ideal mixed flow or plug flow reactor (Levenspiel, 1979), i.e. in the mixed flow case the effluent tracer concentration (Y) decreases exponentially with time following a step down in influent tracer concentration:

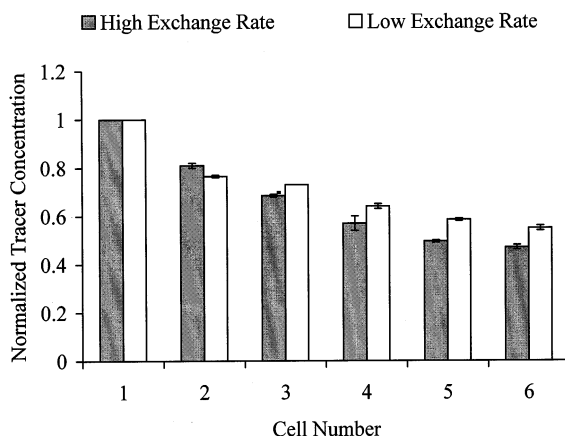


Fig. 4. Normalized tracer concentration at steady-state versus sample location with the tracer introduced exclusively in cell 1.

$$Y = \Delta C / \Delta C_{\max} = e^{-\theta} \quad (7)$$

where

$$\theta = \Delta t / \bar{t}. \quad (8)$$

Conversely, in a plug flow reactor, the tracer concentration returns immediately to the influent baseline concentration at time $t = \bar{t}$ (one complete exchange). Performance of the test tank (Fig. 3), approximates that of a mixed flow reactor and deviated substantially from the response predicted for a plug-flow reactor. Corresponding $D/\mu L$ values (Table 1) ranged between 0.27 and 0.39, indicating again that substantial mixing occurs in the vessel ($D/\mu L > 0.01$) but less than that expected in an ideal reactor (Levenspiel, 1979). The presence of fish at the water flow rate of 379 l/min decreased mixing as indicated by $D/\mu L$ and reduced the variables \bar{t}_c / \bar{t} , σ^2 and σ^2 / \bar{t}_c (Table 1). These effects were statistically significant ($P < 0.05$) except for the ratio \bar{t}_c / \bar{t} and in general agree with the effects of channel catfish on tank performance described by Watten and Beck (1987). Watten and Beck hypothesized that fish influence RTD by moving in and out of stagnant regions within the reactor. This movement would act to increase the degree of interchange between adjacent regions thereby reducing the time required to purge the tracer completely from the tank. The active tank volume measured ranged from 77 to 100% of total volume with the greatest ratio occurring at 502 l/min. The ratios calculated are similar to those reported for two alternative mixed flow type rearing vessels (Watten and Beck, 1987; Watten and Johnson, 1990) — the cross-flow tank (73–87%) and the circular tank (77–79%). The water exchange rate effect on active tank volume was significant ($P < 0.01$) but exchange rate did not influence the other RTD performance indicators.

Fig. 4 gives the mean normalized Cl^- concentration in all cell effluents at steady-state when Cl^- was introduced through one of the vertical pipe segments serving cell 1. The drop in Cl^- measured along the longitudinal axis of the tank was described by an exponential model established using least-squares regression analyses:

Exchange rate = 1.0/h

$$\ln(Y) = 0.0321 - (0.112X)$$

$$R^2 = 0.93, \quad \text{S.E.} = 0.056, \quad P < 0.001. \quad (9)$$

Exchange rate = 1.3/h

$$\ln(Y) = 0.109 - (0.115X)$$

$$R^2 = 0.96, \quad \text{S.E.} = 0.054, \quad P < 0.001. \quad (10)$$

Models (Eq. (9)) and (Eq. (10)) indicate substantial mixing occurs between adjacent cells. Hydraulic behavior of this type is unique and may be useful in tempering the negative effects of non-uniform application of therapeutants or distributions of fish like that observed in baffled raceway systems (Boerson and Westers, 1986; Kindschi et al., 1991).

Proposed Reactor Model

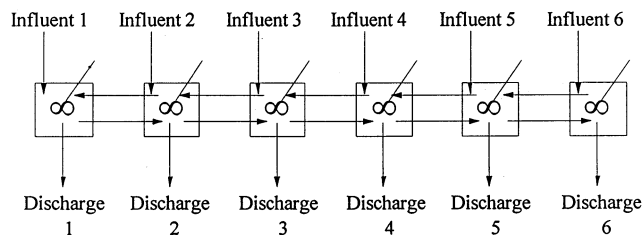


Fig. 5. Proposed reactor model for the mixed cell rearing unit.

Fig. 5 gives the reactor model developed for the test tank based on results from RTD and Cl^- profile analyses. The model proposed shows mixing within each cell as well as that observed between adjacent cells. This model, when used with the Cl^- profile data (Fig. 4), allows calculation of cell interaction rates given that at steady-state the mass addition rate of Cl^- must equal the mass discharge rate. The mass discharge rate across all cells j ($n = 6$) is:

$$\text{MD} = \sum_{j=1}^n ((C_i - C_{\min})Q)_j. \quad (11)$$

For the test case where Cl^- was introduced only into cell 1, the net flux (NF) across the cell 1 – cell 2 boundary must equal the sum of the mass discharged from cells 2–6. This is equivalent to

$$\text{NF} = \text{MD} - ((C_i - C_{\min})Q)_{\text{cell } 1}. \quad (12)$$

When nozzle flow matches center drain discharge, movement of water from cell 1 into cell 2 must match, at steady state, movement from cell 2 into cell 1. Movement of water in either direction is then fixed by the Cl^- concentration difference across the cell boundary assuming the active volume of each cell is mixed:

$$\text{CER} = \frac{\text{NF}}{(C_i - C_{\min})_{j=1} - (C_i - C_{\min})_{j=2}}. \quad (13)$$

This calculation procedure was followed for each cell boundary using Cl^- profile data established at both test inflow rates (Fig. 6). Calculated CER averaged 1769 and 1559 l/min at 1.0 and 1.3 exchanges/h, respectively. The effect of inflow rate on CER was not significant ($P > 0.05$). The CER mean of all calculations (1664 l/min) indicates movement across each cell boundary exceeds tank inflow rates by a factor of 3.9.

Measured current velocities averaged 0.14 m/s at surface (S.D., 0.059), 0.12 m/s at mid-depth (S.D., 0.035), and 0.12 m/s near floor level (S.D., 0.045). Depth effects on velocity were significant in cell 4 ($P < 0.05$) but not cells 5 and 6. The grand mean of current measurements (0.13 m/s) represented 3.7% of inlet jet velocities calculated given orifice diameter and water flow rate. This is less than the 20%

reported in general for circular tank designs (Skybakmoen, 1989). Differences reflect, no doubt, increased drag associated with forced distortion of circulating cells within the test tanks rectangular boundaries. Nevertheless, the pressure requirement of the influent manifold was low (1.32 m gage) resulting in a favorable energy demand of 6.7 W/m³. This ratio is similar to the 7.2 W/m³ calculated for the cross-flow tank (Watten and Johnson, 1990) when operated at a similar surface velocity (0.13 m/s) and volume (20.3 m³). Both designs have minimized energy requirements through use of a large number of uniformly distributed influent jets (Fox and Gex, 1956). Jet induced rotation within cells of the test tank provided a radial current that directed settleable solids across cell floors to center drains. Hence fecal solids released in cell 1 are not required to traverse the length of the vessel prior to removal as in the conventional plug-flow operating mode. Youngs and Timmons (1991) provide an equation that correlates particle diameter (d) and specific gravity (G) with required scouring velocity

$$V_{SC} \geq 1/2d^{4/9} (G-1)^{1/2}. \quad (14)$$

This correlation is conservative given that it ignores the positive effect of fish activity on particle transport. With V_{SC} set equal to the tank mean of 0.13 m/s, and using a G of 1.19 from Chen (1991), Eq. (14) predicts movement of particles less than 4.5 mm in diameter. Benthic shear stress (μ^*) corresponding to the mean surface velocity was 0.04 N/m². This exceeds μ^* values required to move and suspend organic matter including feed pellets (Peterson, 1999). Accordingly, feed and fecal solids produced by our lake trout (mean fish weight 895 g) did not accumulate in the test tank during the 148 day acclimation period. This characteristic provides a savings in labor requirements while also circumventing the negative

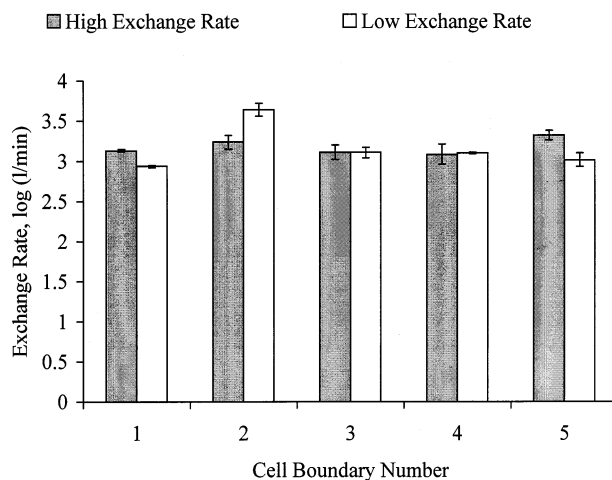


Fig. 6. Calculated cell boundary exchange rates corresponding to Fig. 4 data sets.

effects of solids accumulation, e.g. an increase in biochemical oxygen demand and secondary ammonia production. Beyond particle transport, current velocity plays an important role in establishing cohort performance (Ross and Watten, 1998). Forced swimming improves fish growth, disease resistance, and reduces oxygen consumption rates (Besner and Smith, 1983; Leon, 1986; Totland et al., 1987). Woodward and Smith (1985) reported forced swimming of rainbow trout at 1.5 body lengths/s lowered oxygen consumption 20.1% while fish were resting and 14.4% while swimming. Similar reductions, attributed in part to forced exercise, have been reported for tilapia (Watten and Johnson, 1990) and lake trout (Ross and Watten, 1998). Effects of exercise on oxygen consumption reflect increased white muscle activity (Nahhas et al., 1982), improvements in cardiac output and enhanced oxygen carrying capacity of the blood (Woodward and Smith, 1985). Given that dissolved oxygen is often the first environmental variable to limit production, reduced rates of oxygen consumption can increase proportionally tank production potential at a fixed water inflow rate (Westers and Pratt, 1977; Watten, 1994). Allowable current velocities (salmonids) expressed in terms of body lengths/s decrease with increasing fish length (Youngs and Timmons, 1991):

$$V_{\text{safe}} \leq 10.56/\text{TL}^{0.37}. \quad (15)$$

Eq. (15) predicts the measured current velocity mean (0.13m/s) is safe when fish length (TL) is greater than 2 cm. While the velocity mean is about 24 times that predicted for operation in the plug-flow reactor mode, greater velocities (m/s) may be desirable with increasing TL. Application of the principles of similitude and results of early studies of jet forced circulation suggest higher velocities could be achieved through one or more of the following: (1) reduce fixed surface area – volume ratios; (2) increase water exchange rate; (3) increase jet velocity; and (4) increase number of jets (Ali and Pateman, 1981; Fox and Gex, 1956; Imam et al., 1988; Sobey and Savage, 1974). It may also be desirable to substitute the test tanks floor drains with dual-drains as described by Timmons et al. (1998). Here, solids exiting the tank are concentrated in 5–20% of the total discharge allowing reductions in scale of solids separation equipment sensitive to hydraulic loading such as microscreens or settling basins. Further, tank construction could be simplified by combining cell discharges in one large drain running down the longitudinal axis of the vessel. This modification requires a drain diameter and orifices sized to ensure uniform collection of water from each cell.

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